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14. ABSTRACT

This paper describes the results of the characterization of Fiber Optic (FO) Bragg Gratings (BG) for detection of high frequency ultrasonic waves. The ultimate goal of this effort is to determine the sensitivity of these FO sensors for Acoustic Emission (AE) detection. Ultrasonic AE signals are typically generated in materials when pre-existing crack in the material grows in length. In order to characterize these sensors, FOBG's of different lengths were bonded to piezoelectric crystals of comparable thickness. The lengths used in this study where 1 mm, 2mm, 4mm and 6mm. This allowed us to study the effects of the grating-length to ultrasound-wavelength ratio as they relate to detection sensitivity. A large number of frequencies (ranging from 10kHz to 2MHz) were used in the study to determine the effect of frequency on system sensitivity. To enhance detection sensitivity, a matched Bragg grating was used in the demodulation side of the detection system. We have also performed theoretical modeling of the acoustic emission detection by fiber Bragg gratings using coupled wave theory. Our modeling results will be compared with the experimental findings. Work is currently underway to apply this detection technique to monitor acoustic wave emission from cracking and sudden damage in composite polymer plates.

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optical fiber Bragg gratings, acoustic emission detection

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High Frequency Ultrasonic Wave Detection Using fiber Bragg Gratings

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ABSTRACT

In this paper we describe the result of the characterization of Fiber Optic (FO) Bragg Gratings (BG) for detection of high frequency ultrasonic waves. The ultimate goal of this effort is to determine the sensitivity of these FO sensors for Acoustic Emission (AE) detection. Ultrasonic AE signals are typically generated in materials when a pre-existing crack in the material grows in length. In order to characterize these sensors, FOBG's of different lengths were bonded to piezoelectric crystals of comparable thickness. The lengths used in this study where 1mm, 2mm, 4mm and 6mm. This allowed us to study the effects of the grating-length to ultrasound-wavelength ratio as they relate to detection sensitivity. A large number of frequencies (ranging from 10kHz to 2MHz) were used in the study to determine the effect of frequency on system sensitivity. To enhance detection sensitivity, a matched Bragg grating was used in the demodulation side of the detection system. We have also performed theoretical modeling of the acoustic emission detection by fiber Bragg gratings using coupled wave theory. Our modeling results will be compared with the experimental findings. Work is currently underway to apply this detection technique to monitor acoustic wave emission from cracking and sudden damage in composite polymer plates.

Keywords: optical fiber Bragg gratings, acoustic emission detection.

1. INTRODUCTION

Since the advent of photo-induced Bragg gratings in optical fibers[1] in 1978, Bragg fiber gratings (FBG) have found many applications in telecommunication and in sensing. This is especially true since the development of the external Bragg grating writing technique[2], which had more flexibility in the choice of the Bragg period. Since then, and due to their unique properties, a number of sensing concepts have been proposed and demonstrated. Most of these sensors are configured as back reflectors. A more general configuration, a Tapped Bragg Grating (TBG), was also demonstrated[3]. Bragg gratings have several advantages over other type of fiber optic sensors. The main advantage is that several Bragg grating sensors can be placed in a single fiber optic line and be independently addressed. BG's are also immune to EMI, the output of the BG is absolute, (it has a built in reference length scale, the Bragg Period, relative to which strains are measured) and BG sensors are very small (5 mil diameter x 1/10" long) allowing them to be placed in small places or even embedded within composite materials, wile strain sensors are bulky. As a result, Bragg gratings are currently being considered for smart material applications, where an entire panel is interrogated with a single fiber. The physical quantity that a Bragg grating measures is strain. The output readout from this device is linear and absolute. The strain sensitivity can be better that 1 μ strain while the maximum value is defined by the fiber limit. The main problem associated with this device is its fabrication cost. Long-period gratings (LPG) were recently developed. This device couples light from a core-guided mode to a cladding-guided mode. Since cladding modes are sensitive to the environment surrounding the fiber, these devices are ideal for monitoring the chemical changes in the surrounding environment. Other types of fiber optic sensors exist such as the Fiber Fabry-Perot (FFP) interferometer, Tapped Bragg Gratings (TBG), and Bi-Conical Tapered (BCT) Fibers. Each type of sensor has its advantages and is finding new military and commercial uses. Before implementation into military and

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civilian applications, such as airplane structural health monitoring, these fiber sensors must be tested for durability and reliability in the hostile environment. For example, one must ascertain the survivability of fibers under fatigue.

We have recently embarked on an experimental program of using optical fiber Bragg gratings to detect acoustic emission (AE) signals. As is well-known, when cracks initiate and develop in a structure due to fatigue and loading[4], there are always associated bursts of acoustic energy in the form of ultrasonic waves emanating from the cracks and propagating through the structure. Thus, detection of AE signals can give early indication and warning of structural failure. To date, most AE detection apparatus are based on application of ultrasonic transducers, which is not easily integrated into the structure itself for *in situ* detection and monitoring. On the other hand, fiber Bragg gratings are easily embedded in the structure without affecting the structural integrity of the structure itself, or surface-mounted nonintrusively. Furthermore, fiber gratings are ideal for multiple sensor applications as many of these gratings can be employed either in series or in parallel. In this aspect, many of the multiplexing technologies developed in the telecommunication industry can be directly applied. These include time division multiplexing and wavelength division multiplexing. Thus, it is reasonable to envision in the near future of embedding hundreds of fiber Bragg gratings on an airplane wing to continuously monitor the structural integrity of the wing in flight. To be sure, there is a multitude of technical challenges that must be overcome to make this a reality. First, the detection sensitivity must be very high. This is especially important since AE events are usually buried in a noisy environment. Secondly, detection speed must be high enough to capture instantaneously most of the frequency contents of an AE signal. Thirdly, one must develop a sophisticated computer-based real-time data acquisition, processing, and analysis system in order for the AE sensors to be truly effective. These challenges must be overcome through systematic experimentation in conjunction with simulation and modeling. In this paper, we report our recent work in trying to answer some of the questions and overcome some of the obstacles on the road to fiber Bragg grating based AE detection.

2. EXPERIMENTAL SETUP

To establish the detection sensitivity and speed of the fiber Bragg grating sensors, we performed a series of experiment with the sensors using controlled generation of ultrasonic signal. The latter was accomplished employing PZT acoustic resonators driven by a pulse generator (Ritec RAM-10000). The fiber gratings are glued to the side surface of the acoustic resonator, so that when the resonator is set into vibration in its thickness-extension mode, the fiber grating is stretched and shortened periodically at the frequency of the acoustic resonator. A super-radiant luminescent light source was employed to send light (centered at 1300 nm, with a spectral width of 30 nm, and a peak power of 1.3 mW) down the fiber. A high-speed photodetector converts the light signal back to electrical signal, which is displayed on a digital oscilloscope. (See Figure 1 for a block diagram of the experimental setup.)

To investigate the full range of parameter space, several PZT resonators of different thickness (thus different resonant frequencies) were employed. Likewise, fiber Bragg gratings of various gage lengths were used. Table I summarizes the physical attributes and resonant frequencies (mostly in the thickness extension mode) of the PZT resonators.

Table 1. PZT acoustic resonators used in the experiment.

Resonators	Dimensions	Resonant Frequencies
C-8000 a	Disk of diameter 1.5", 0.16" thick	550 kHz
C-8000 b	Disk of diameter 2", 0.08" thick	1.05 MHz
C-8000 c	Bar of 1"x1"x 0.04"	2.1 MHz
C-8000 d	Bar of 1/2"x1"x 0.25"	330 kHz

Fiber Bragg gratings of different gage lengths were used in this experiment. These include gage length of 1 mm, 2mm, 4mm, and 6 mm. All have center wavelength of 1300 nm and reflectivity greater than 90%, but with different reflection peak width. Table 2 summarizes the physical properties of the fiber Bragg gratings used.

Table 2 Fiber Bragg gratings used in the experiment

Gage length (mm)	Center wavelength (nm)	Spectral width (nm)
1	1300	1.04
2	1300	0.53
4	1300	0.26
6	1300	0.33

In the experiment we attach the fiber Bragg grating to the side surface of the PZT acoustic resonator using "super glue" (Adhesive Cyamacrylate). Electrodes are attached to the two opposite faces of the PZT resonator that are connected to a high-power pulse generator (Ritec RAM 10000). The latter is capable of generating well-shaped sinusoidal wave trains of arbitrary number of cycles between 0.1 MHz and 50 MHz. The pulse amplitude can be as high as a few thousand volts, although in our experiment we never employed more than a hundred volts.

The light source used in the experiment was a superluminescent diode with center wavelength of 1300 nm and a spectral width of about 40 nm. Total integrated power is about 1.5 mW. The power level is continuously tunable by changing the drive current. The photodetectors used are New Focus low-noise, high-speed photoreceivers, with bandwidth of 125 MHz.

Light is sent out by the SLED down a single- mode optical fiber to a 3 dB 2x2 coupler. One of the output arms of the coupler is connected to the fiber Bragg grating that is glued to the PZT resonator. The reflected light goes into a matching fiber Bragg grating that serves as the demodulator. Light signal from the demodulator goes into the photodetector whose electrical output is fed into a digital oscilloscope.

As the PZT resonators have resonant frequencies ranging from 200 kHz to 2 MHz, we were able to investigate the response of our fiber Bragg grating sensors to AE signals over the entire frequency domain mentioned above. However, the frequency response is not uniform across the frequency domain, as different resonators have quite different resonant frequency and displacement characteristics. Most of our data were taken near resonance, for the response falls sharply away from resonance.

For demodulating the optical response signal, we used a matching fiber Bragg grating. We found that this demodulator is very sensitive to small optical intensity change at extremely high speed. To obtain the optimal modulation/demodulation combination, we investigated all possible combinations of the fiber Bragg gratings with various gage lengths.

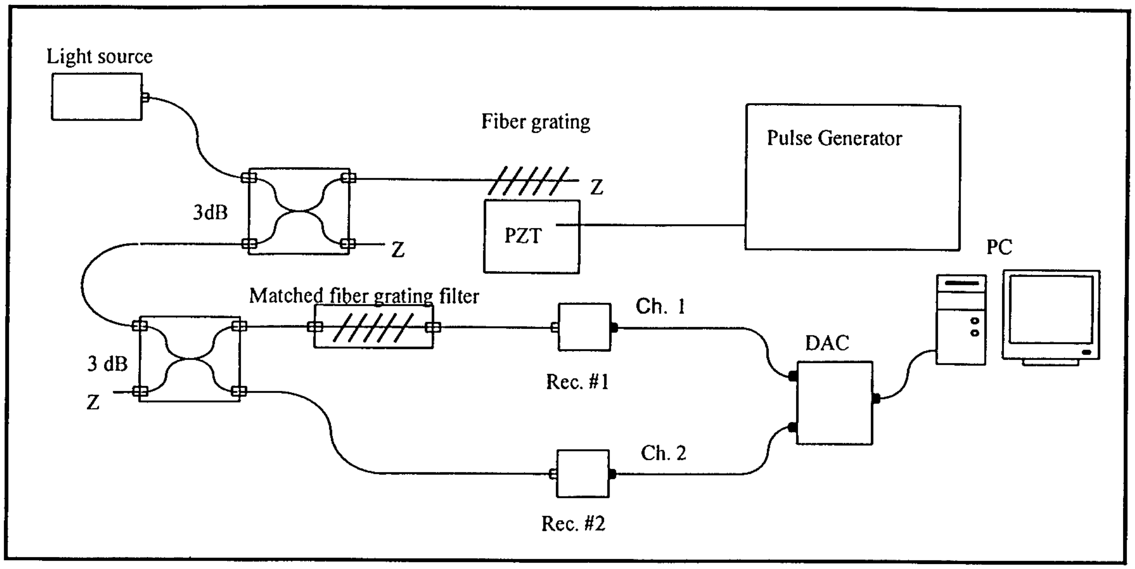

Figure 1 Block Diagram of the experimental setup.

3. EXPERIMENTAL RESULTS

Experimental data were taken in the form of photoreceiver voltage response to the light signal. In this, only the AC component is recorded (the DC voltage, of the order of several volts, carries no direct information on the AE signal.) The data taking commences when a trigger signal is received from the pulse generator, which is clocked to coincide with the onset of the sinusoidal wave train. Typically, about 10 cycles of sinusoidal voltage wave is applied, with a typical amplitude of 10 to 100 volts. Figure 2 shows a typical waveform of the signal, the trigger, and the response, at a frequency of 355 kHz. Figure 3 shows the same for a frequency of 1 MHz.

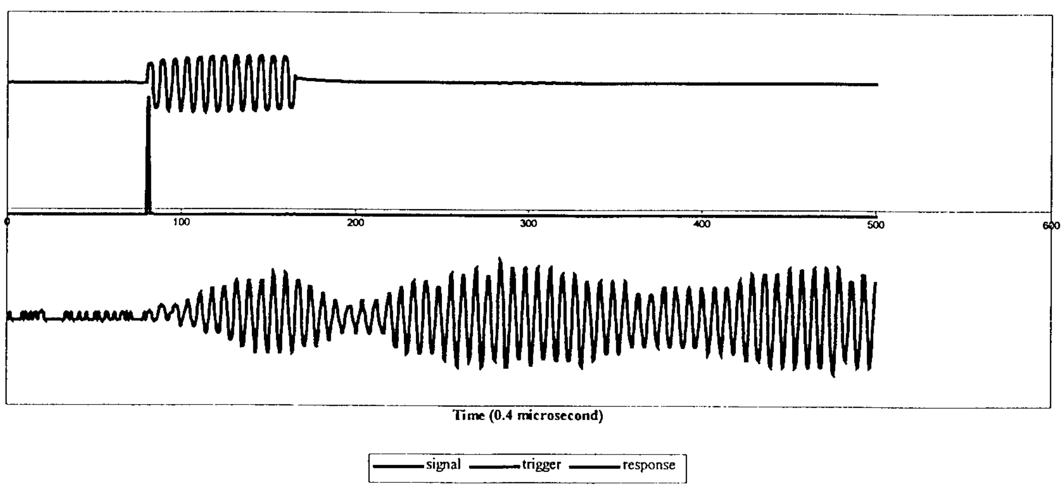

Figure 2 Pulse signal, trigger, and response at 355 kHz.

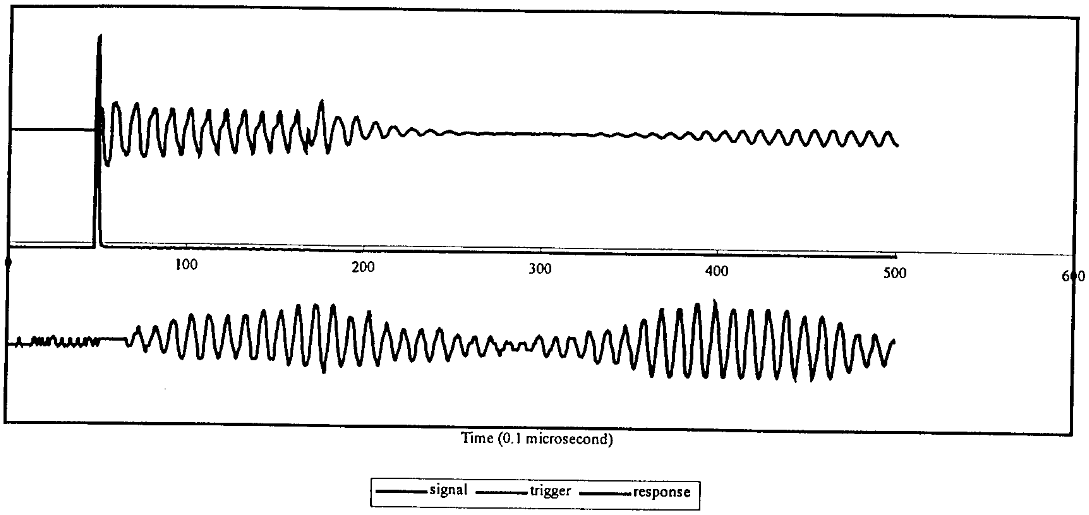

Figure 3 Pulse signal, trigger, and response at 1 MHz.

As pointed out earlier, different combinations of detector/demodulator fiber Bragg gratings lead to somewhat different response level. To find the optimal combination, we have investigated all possible combinations of detection/demodulation fiber Bragg gratings. In table 3, we summarize the response at 525 kHz, for various combinations of modulation/demodulation fiber Bragg gratings.

Table 3 Reponses for various modulator/demodulator combinations at 525 kHz.

Detector/demodulator	1 mm	2mm	4mm	6mm
1 mm	23.44 mV	0	24.69	0
2 mm	5.63	26.25	20.94	13.44
4 mm	2.81	7.81	8.13	16.25
6 mm				

In Figure 4, we show the response of the fiber Bragg grating sensors to AE signals as a function of frequencies. Note that these data were collected from several resonators, as each of them only covers a limited frequency space. The null response regions in the figure are purely of results that we do not have the appropriate resonators, which have resonant frequencies in the given regions.

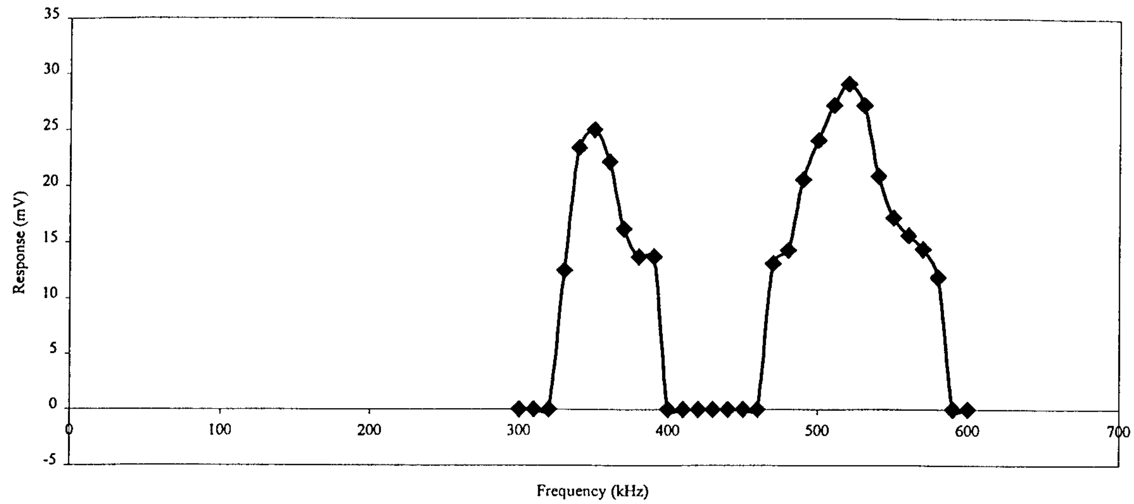

Figure 4 Response as a function of frequencies.

To ascertain the detection limit, we also investigated the minimum light intensity necessary for AE detection by using fiber Bragg gratings. In Figure 5 we show the response as a function of the driving current of the light source. Note that the power output of the light source is roughly proportional to the drive current in the range depicted. Therefore, this set of data may be construed as a relation of response vs. light intensity level.

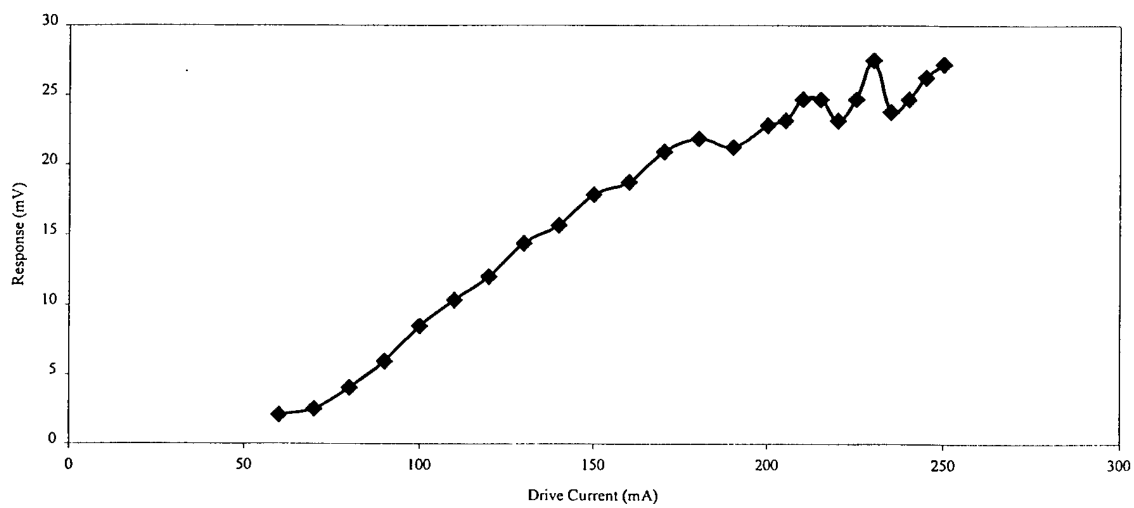

Figure 5 Response vs. the drive current of the light source.

4. THEORETICAL MODELING

In this section we consider theoretically the problem of coupling of an ultrasonic disturbance to light wave propagating down an optical fiber, through a Bragg diffraction grating etched into a section of the optical

fiber. Our approach is based on the coupled wave theory commonly used in discussing co-propagation and scattering of electromagnetic waves[5].

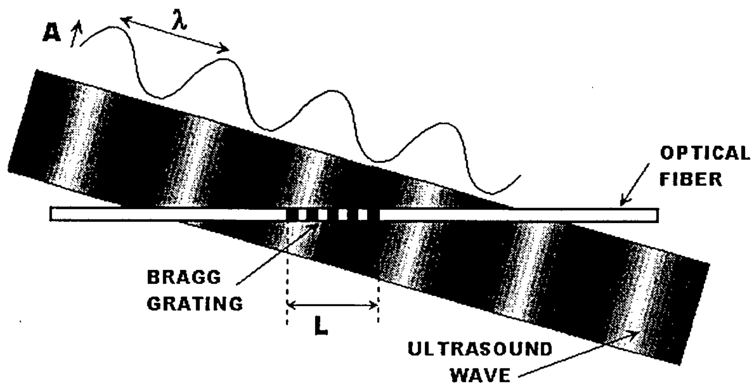

Figure 6 Schematics of interaction of ultrasound wave with light wave going through a fiber Bragg grating.

The question that needs to be answered is, what is the coupling coefficient from a guided mode to another guided mode when a sound wave is superimposed to a Fiber Optic Bragg grating? In the weak coupling approximation one can follow the standard procedure to derive an expression for the coupling from a forward-propagating mode *i* to a backward-propagating mode *j*.

In the presence of the sound wave, the difference in index of refraction will no longer be given by the simple expression for the fiber Bragg grating,

$$n^2 - n_{co}^2 = 2n_{co}n_p \cdot \sin(2\pi / \Lambda_{oB})z$$

since the presence of an ultrasonic wave will change the periodicity of the Bragg grating. n_{co} is the index of refraction of the core and n_p is the amplitude in the variation of the index in the Bragg grating. If the Bragg period at rest is Λ_{oB} and the ultrasonic wave has amplitude is A and the frequency is ω then the new Bragg "period" will be given by

$$\Lambda_B = \Lambda_{oB} + A \cdot \cos(\omega \cdot t - k \cdot z)$$

It should be mentioned at this point that Bragg grating sensors will be more sensitive to extensional waves (or symmetric Lamb waves) than to flexural (or antisymmetric) waves since a transverse displacement of a Bragg line does not change the Bragg period. To first order approximation the coupling from the ith forward-propagating mode to the jth backward-propagating mode, c_{ji}, will be given by

$$\boxed{c_{ij} \cong 2n_p \cdot e^{-i \cdot \beta_j \cdot z} \cdot J_1(\lambda \cdot \frac{A}{\Lambda_{oB}^2}) \cdot \sin(k \cdot \frac{L}{2}) \cdot \sin(\omega \cdot t)}$$

Here *J1(x)* is a first order Bessel function. We have compared the theoretical prediction with our experimental data. Figure 6 depicts such a comparison. Here we plot the response versus the driving voltage of the pulse generator. Note that the physical displacement (the quantity "*A*") in the above equation, is proportional to the driving voltage for the piezoceramic resonators employed.

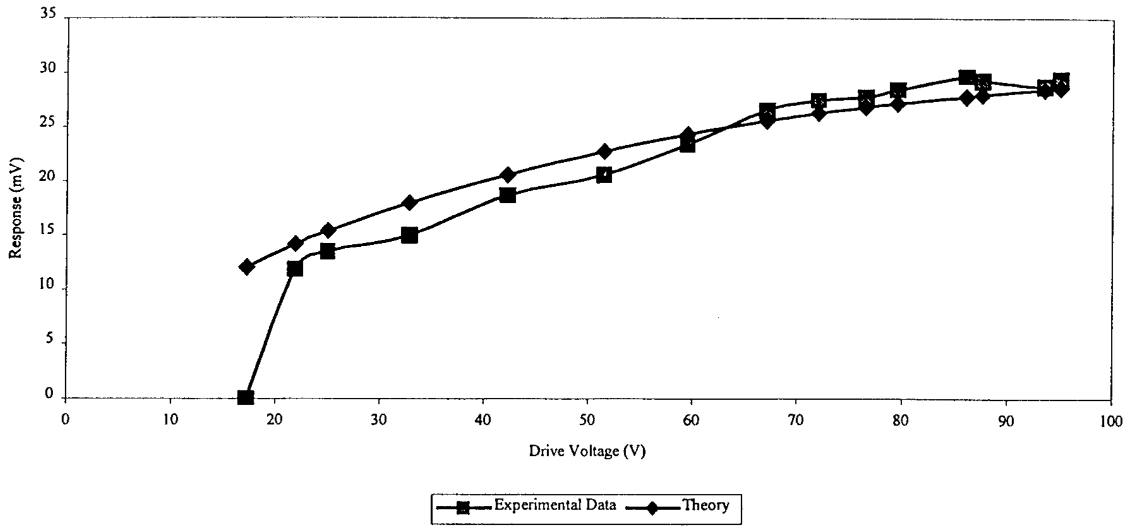

Figure 6 Response versus driving voltage of the pulse generator. Experimental data points are represented by squares, whereas theoretical prediction is given by the diamonds.

5. DISCUSSION AND CONCLUSION

From our experimental investigation a lower detection limit has been established for AE detection using fiber Bragg gratings. The lowest driving voltage employed when a signal is still clearly registered is about 10 volts. This gives a net displacement of the resonator surfaces[6] (relative to each other) of about 2×10^{-11} m. At 2 MHz, the resonator thickness is 0.04", which gives a minimum detectable strain of about 0.02 μ strain. This kind of detection sensitivity is comparable or better than all the currently available methods of acoustic emission detection.

As to the best combination of detection/demodulation by using a pair of matching fiber Bragg gratings, our data show a general trend toward gratings of the same gage length. However, we hasten to add that a deciding factor in the sensitivity is the relative peak positions of the two gratings. Obviously, if the peaks are completely on top of each other, the sensitivity is reduced. By the same token, when the two peaks are two far apart, the scheme fails to work. We are in the process of making the demodulating fiber grating tunable, by employing a stretching apparatus. In this way, a higher sensitivity may be achieved.

In conclusion, we have obtained very promising experimental evidence that fiber Bragg gratings may be used to detect acoustic emission events. This detection method is very sensitive, highly reliable, and can be easily adapted to structural monitoring. As this study is still preliminary, we hope to report more in-depth investigation of AE detection using fiber Bragg gratings in the near future.

ACKNOWLEDGMENTS

This work was supported by the Office of Naval Research.

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High Frequency Ultrasonic Wave Detection Using Fiber Bragg Gratings*

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E. Udd, Blue Road Research, Fairview, OR

*This work was supported by ONR

** Also at Stevens Institute of Technology, Hoboken, NJ

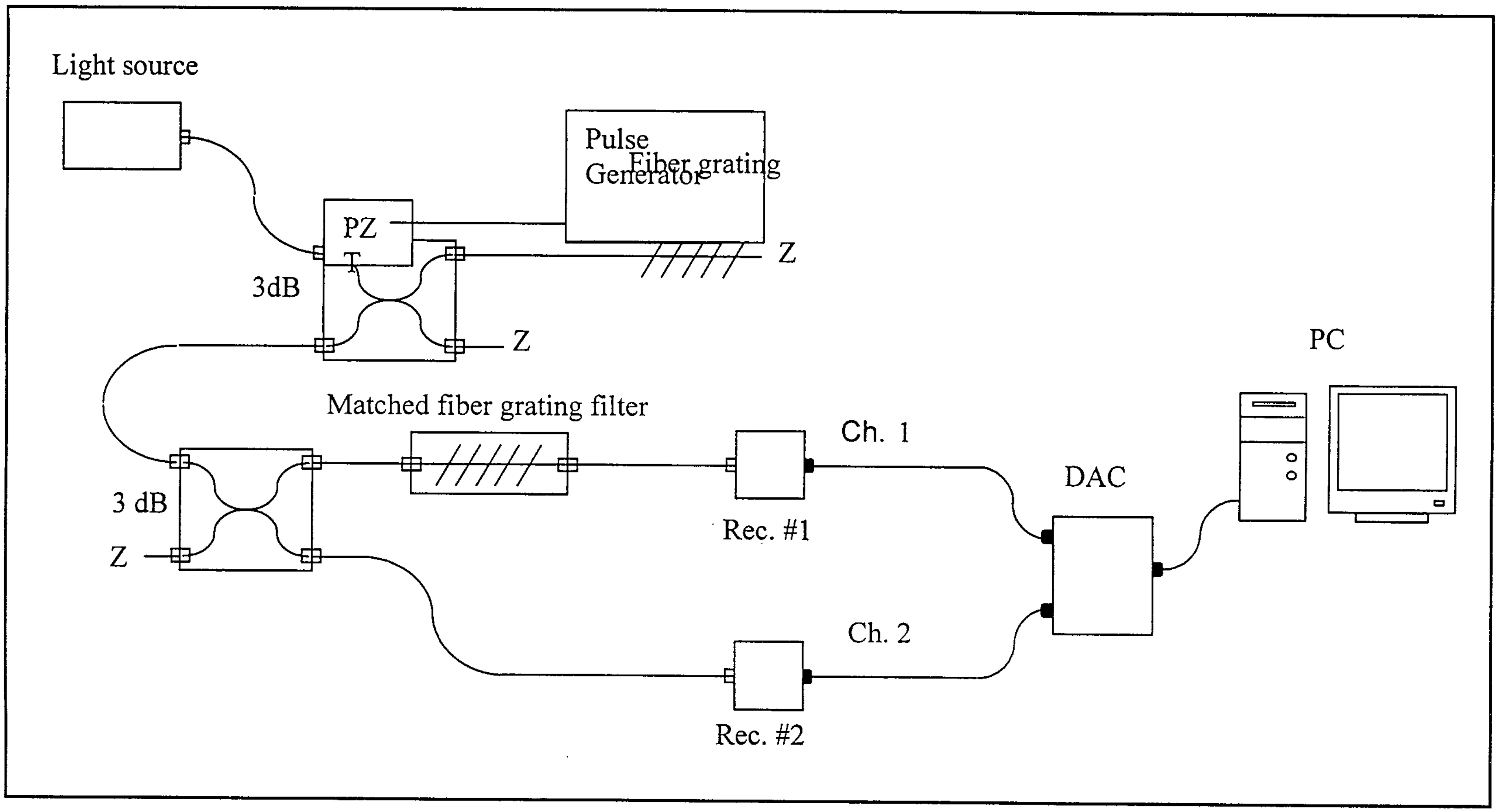
Objective

- To study the feasibility of using fiber Bragg gratings to detect acoustic emissions.
- To establish the limit of sensitivity of detection.
- To establish the frequency limit of detection.
- To evaluate the necessary components and instrument.

Approach

- Use PZT resonators to simulate AE sources
- Bond fiber grating to side surface of PZT resonator
- PZT is driven by pulse generator
- Use a second grating to demodulate the signal
- Several combination of detect/demodulate gratings were investigated

Experimental Set-up



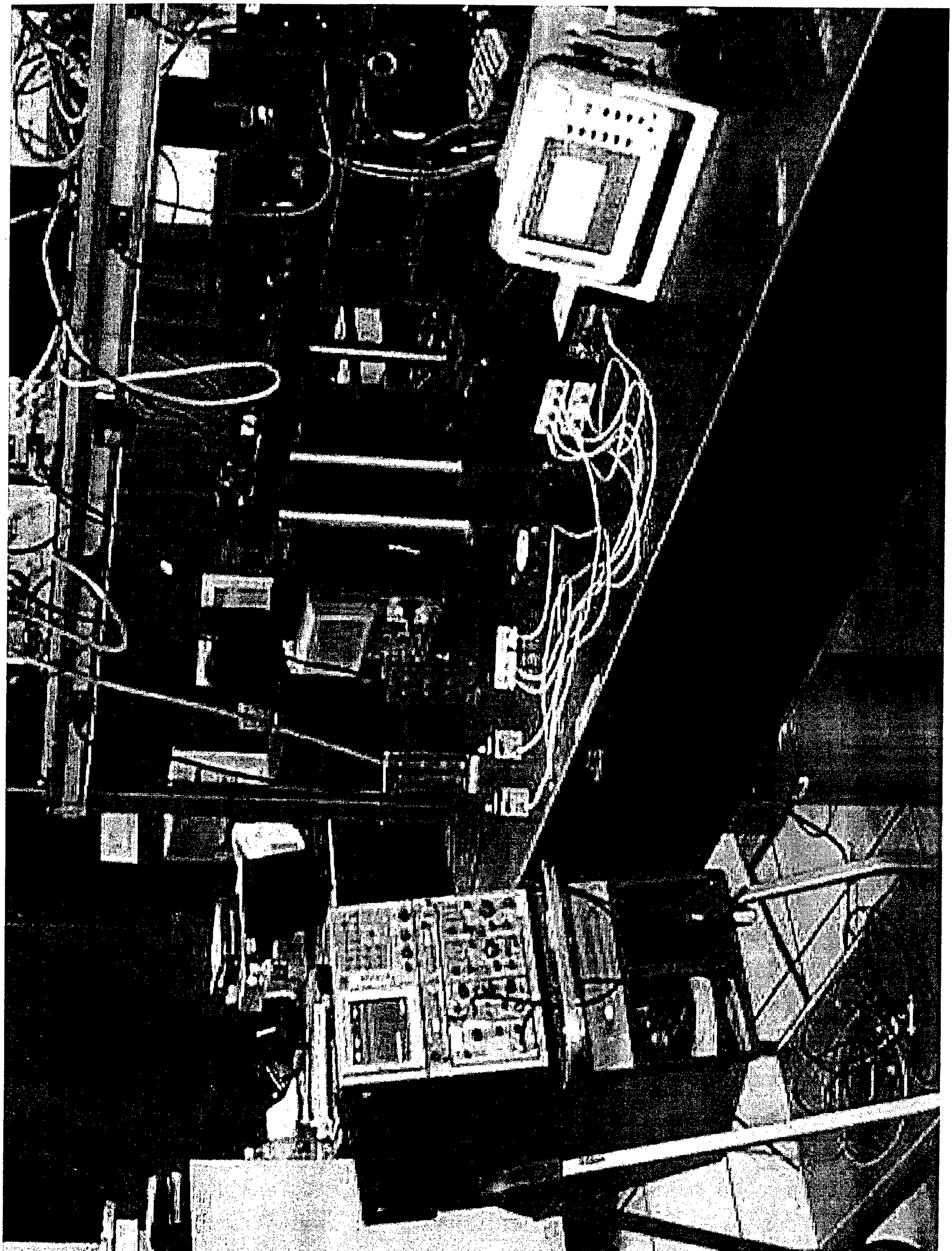


Table 1. PZT acoustic resonators used in the experiment.

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C-8000 c	Bar of 1"x1"x 0.04"	2.1 MHz
C-8000 d	Bar of 1/2"x1"x 0.25"	330 kHz

Table 2 Fiber Bragg gratings used in the experiment

Gage length (mm)	Center wavelength (nm)	Spectral width (nm)
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2	1300	0.53
4	1300	0.26
6	1300	0.33

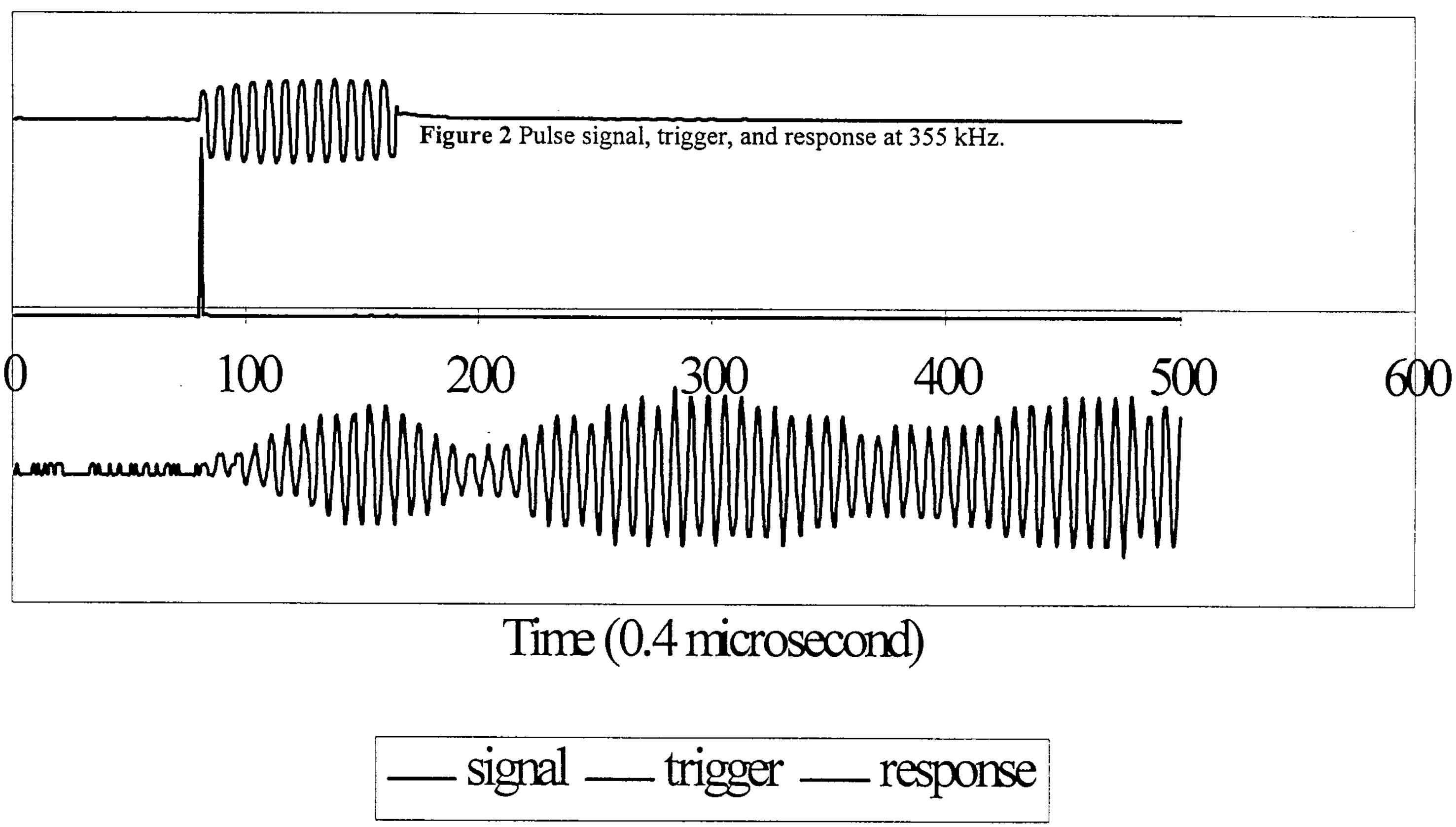
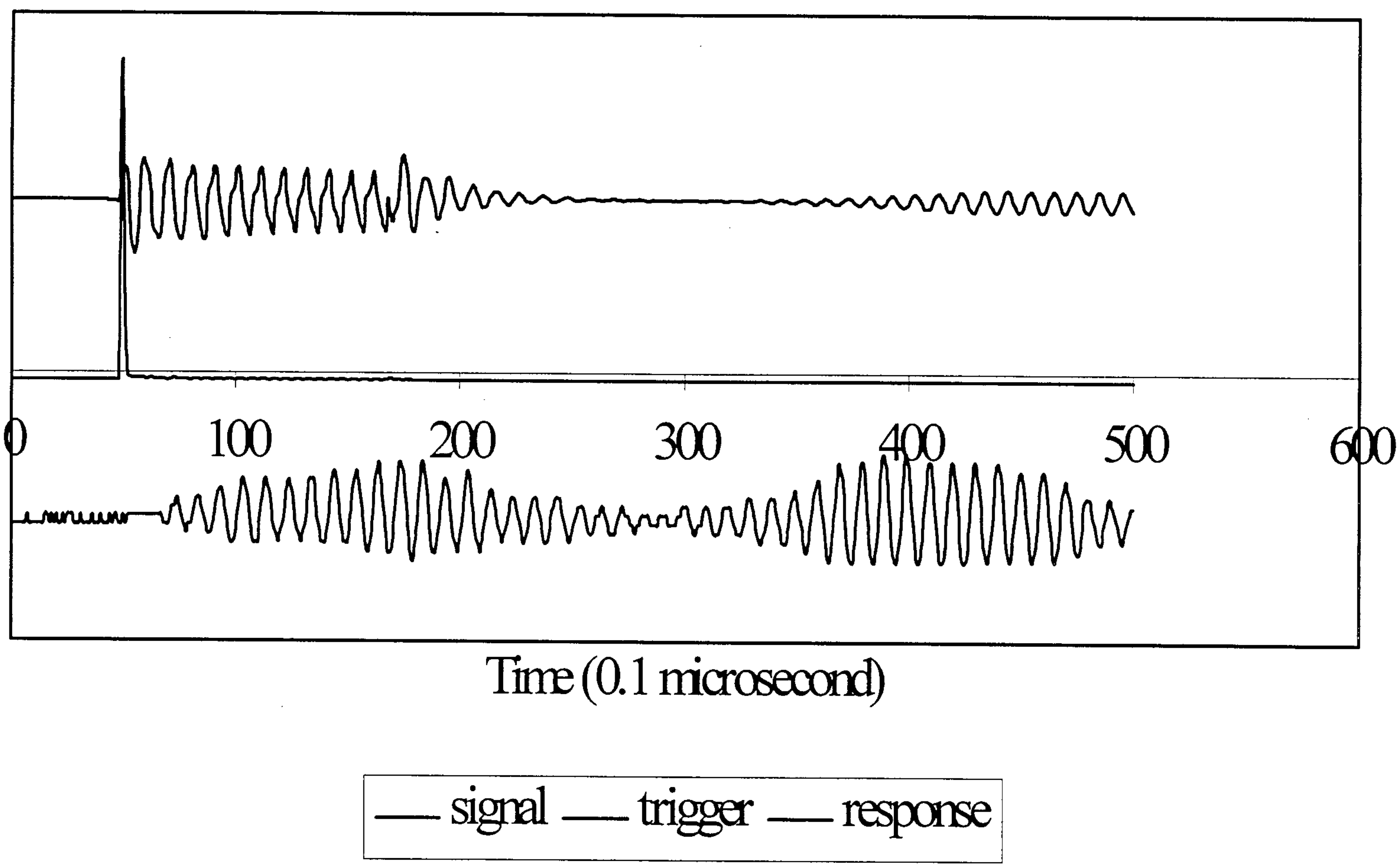


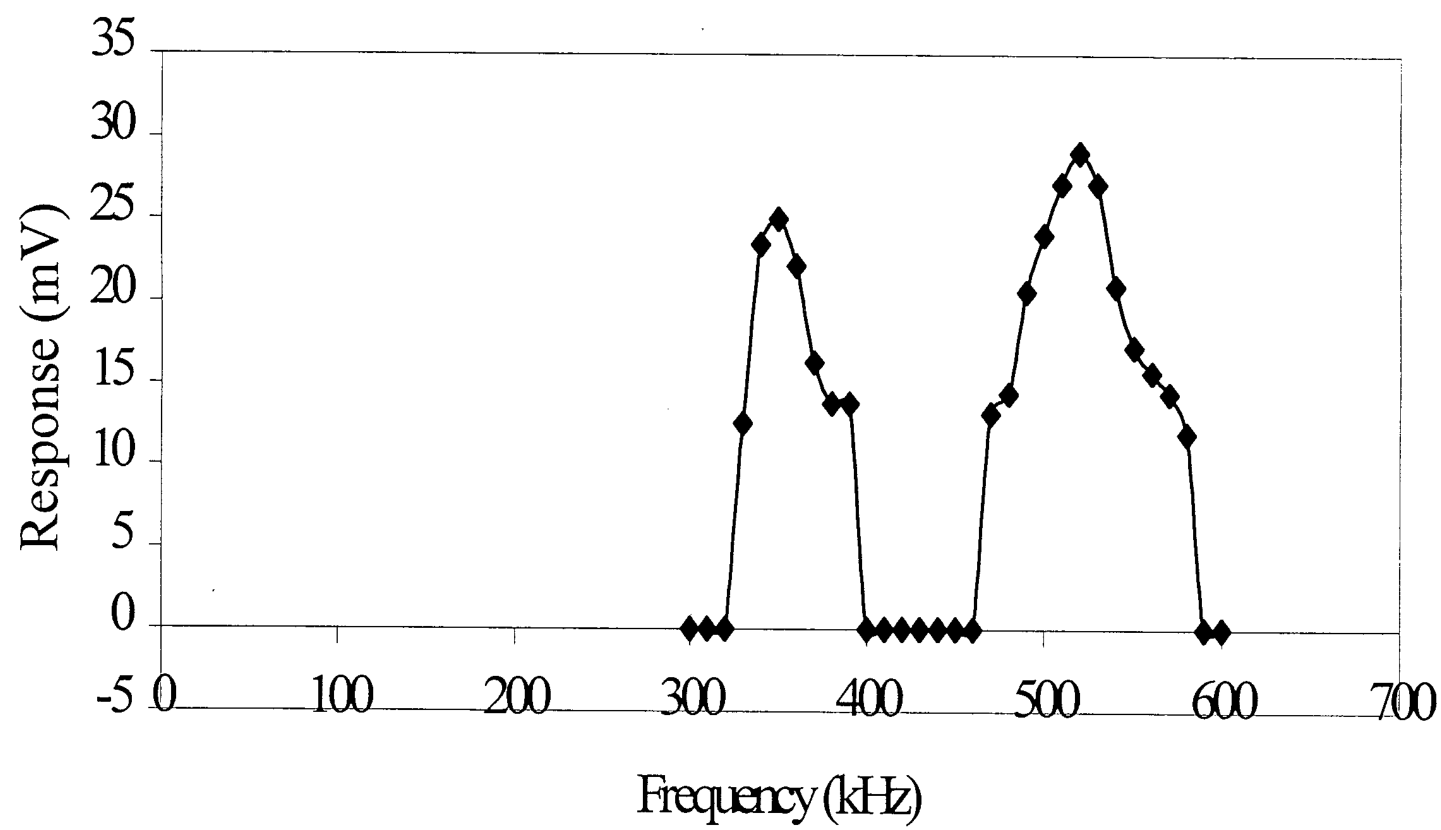
Figure 2 Pulse signal, trigger, and response at 355 kHz.

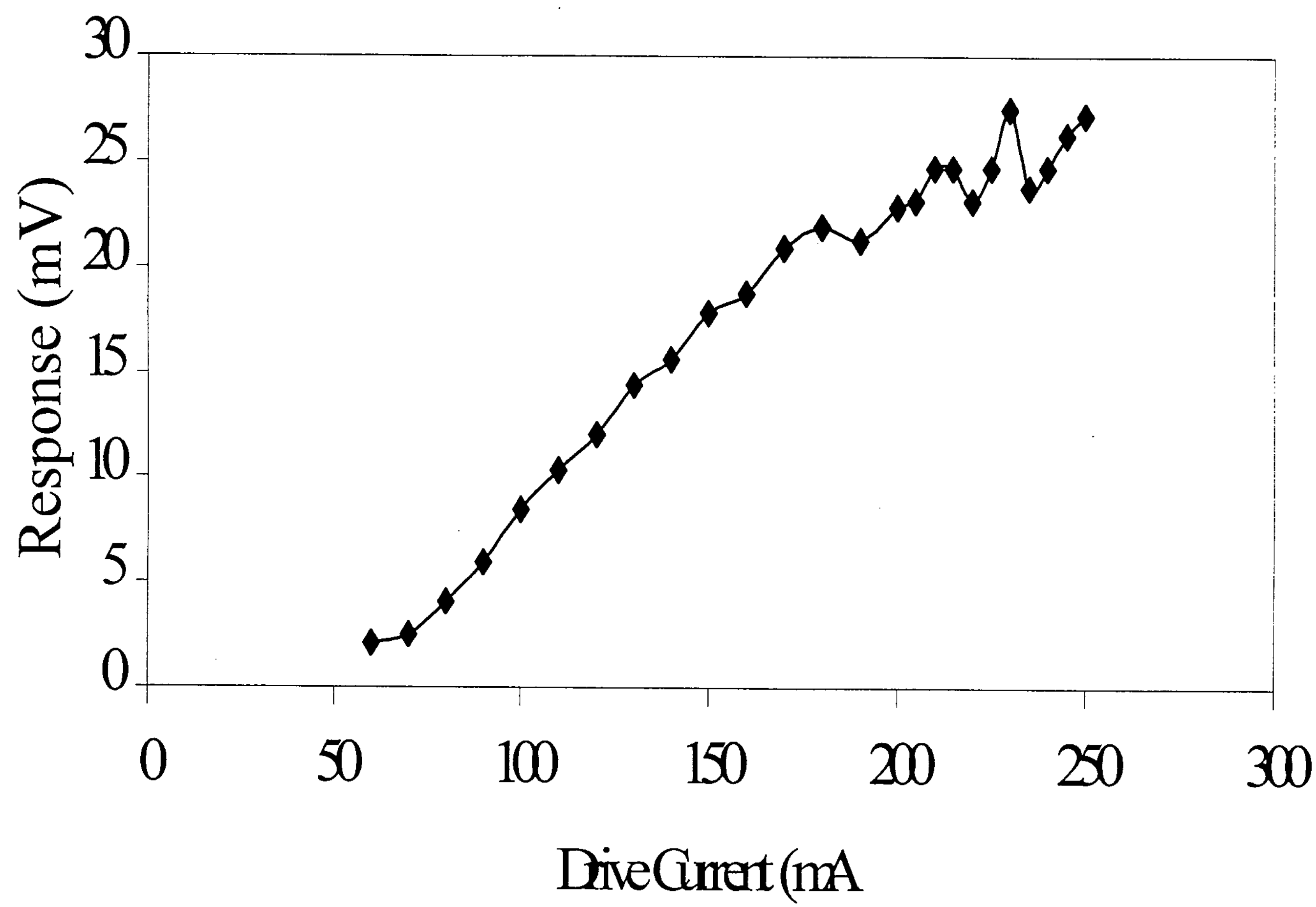


0
100
200
300
400
500
600
Time (0.1 microsecond)
signal
trigger
response

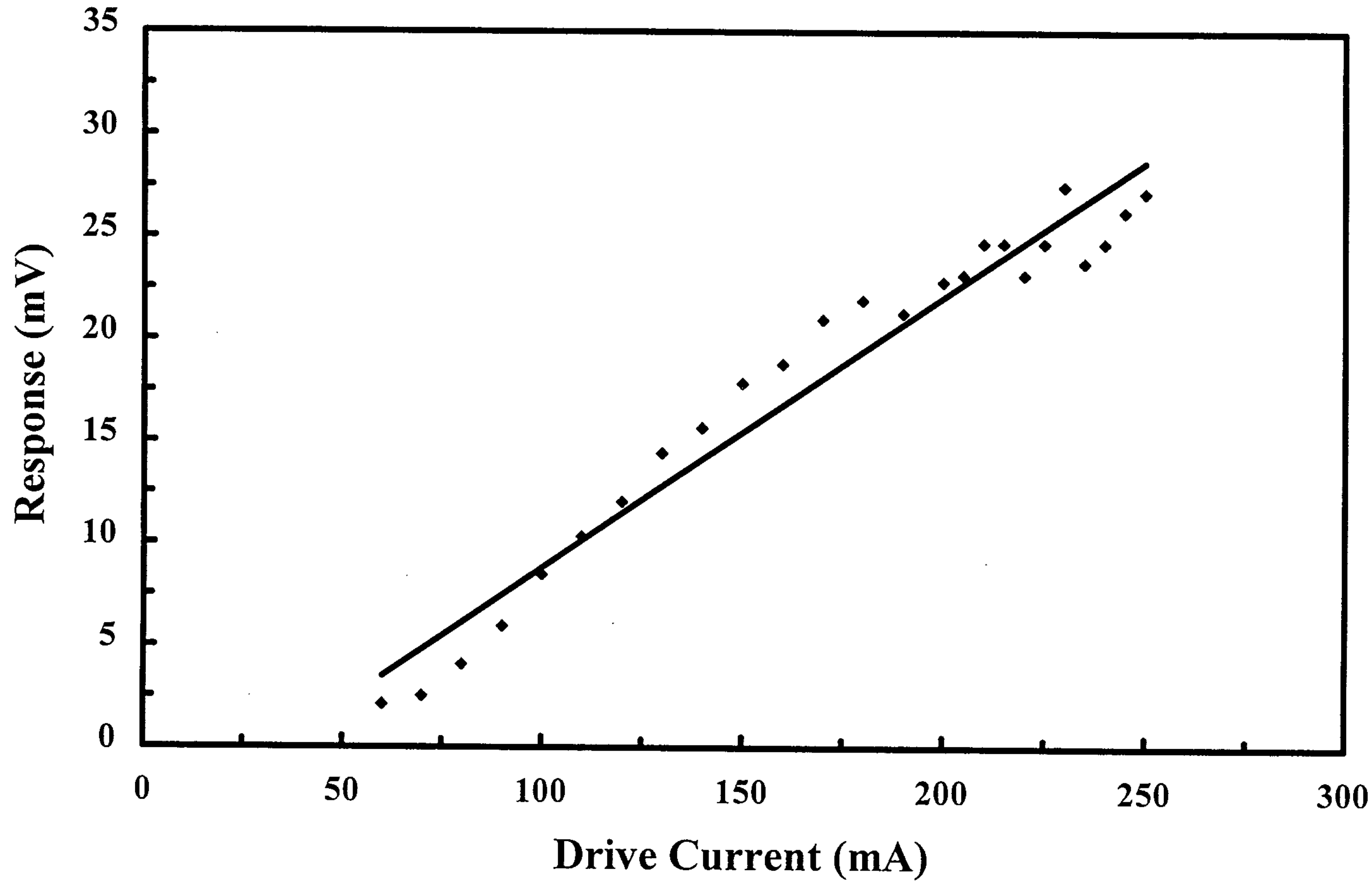
Table 3 Reponses for various modulator/demodulator combinations at 525 kHz.

Detector/demodulator	1 mm	2mm	4mm	6mm
1 mm	23.44 mV	0	24.69	0
2 mm	5.63	26.25	20.94	13.44
4 mm	2.81	7.81	8.13	16.25
6 mm				

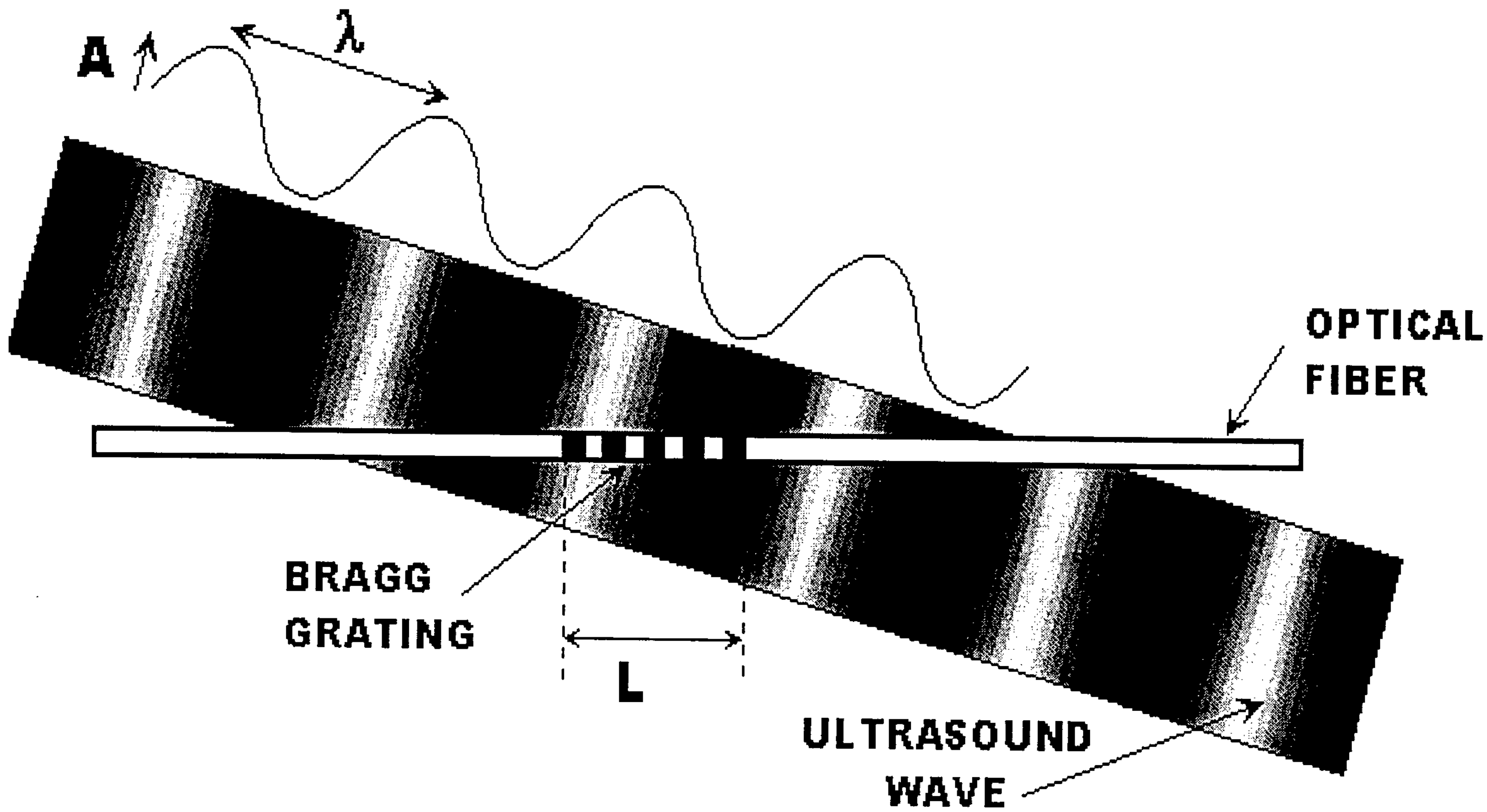

35
30
25
20
15
10
5
0
-5
Response (mV)
0
100
200
300
400
500
600
700
Frequency (kHz)



Response (mV)
30
25
20
15
10
5
0
0
50
100
150
200
250
300
Drive Current (mA



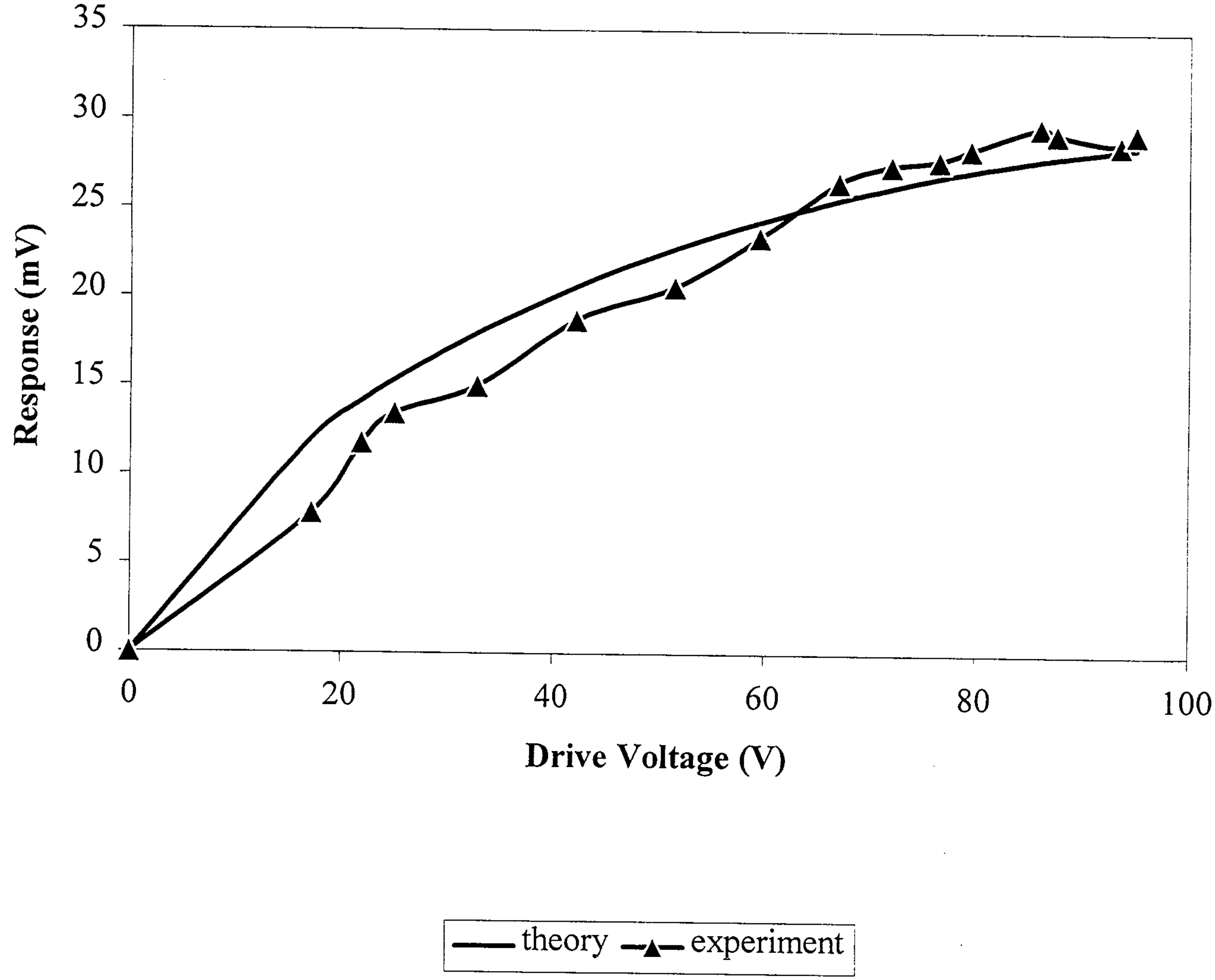
35
30
25
20
15
10
5
0
Response (mV)
0
50
100
150
200
250
300
Drive Current (mA)


A
λ
OPTICAL
FIBER
BRAGG
GRATING
L
ULTRASOUND
WAVE

$$n^2 - n_{co}^2 = 2 n_{co} n_p \cdot \sin(2\pi / \Lambda_{oB}) z$$

$$\Lambda_{\mathrm{B}} = \Lambda_{\mathrm{oB}} + \mathrm{A} \cdot \cos(\omega \cdot \mathrm{t} - \mathrm{k} \cdot \mathrm{z})$$

$$c_{ij} \cong 2 n_p \cdot e^{-i \cdot \beta_j \cdot z} \cdot J_1(\lambda \cdot \frac{A}{\Lambda_{oB}^2}) \cdot \sin(k \cdot \frac{L}{2}) \cdot \sin(\omega \cdot t)$$


35
30
25
20
15
10
5
0
Response (mV)
0
20
40
60
80
100
Drive Voltage (V)
theory
experiment

Summary

- Demonstrated feasibility of using fiber grating to detect AE
- Detected simulated AE events up to 2MHz
- Detection sensitivity about 0.02 micro strain was achieved.
- Simulated fiber grating coupling of light wave with acoustic wave
- Agreement of theory with experiment achieved.